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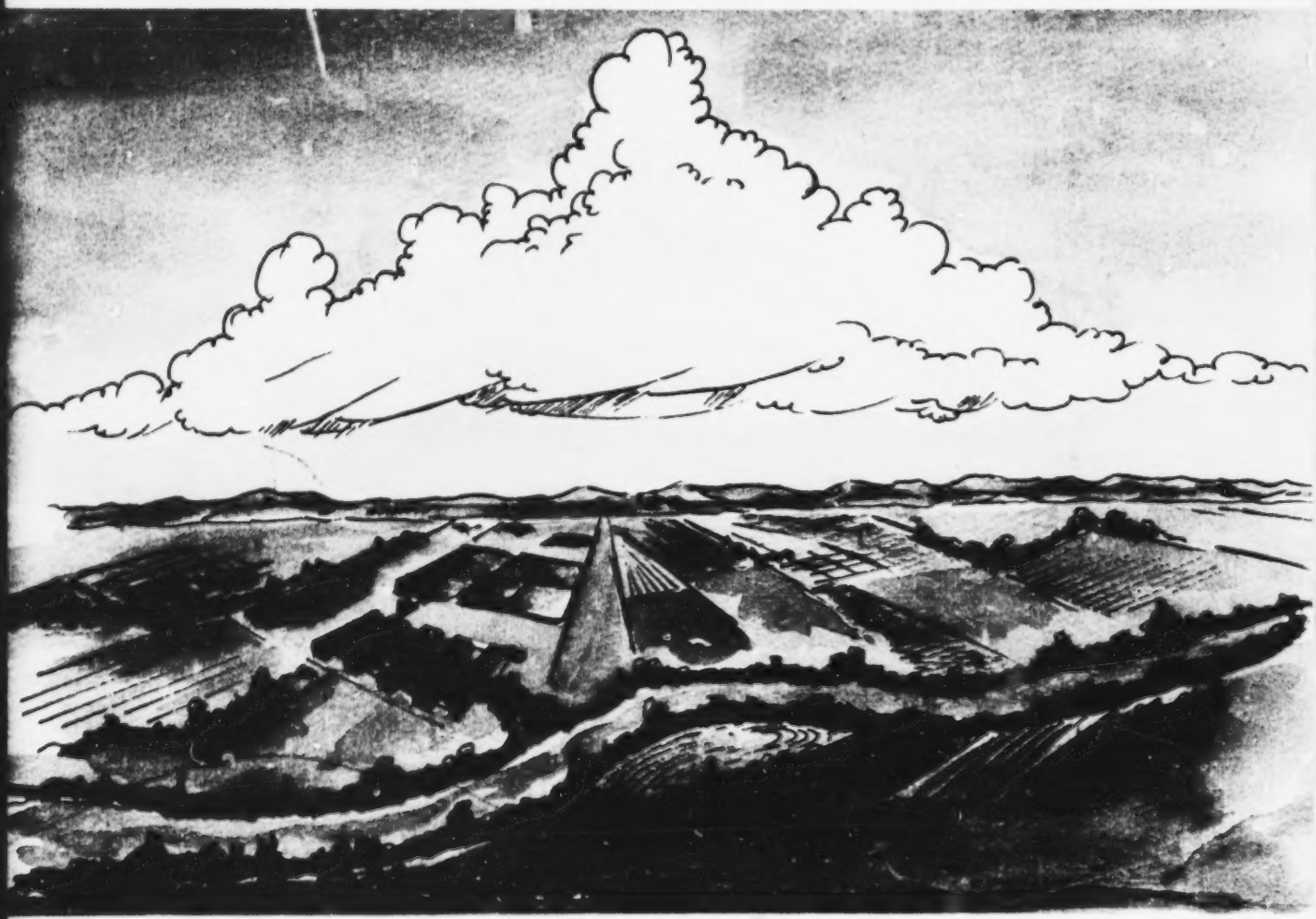
EVALUATION OF TECHNIQUES FOR ALGAE REMOVAL FROM WASTEWATER STABILIZATION PONDS

E. Joe Middlebrooks, Donald B. Porcella, Robert A. Gearheart, Gary R. Marshall, James H. Reynolds, and William J. Grenney



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Utah Water Research Laboratory
College of Engineering
Utah State University
Logan, Utah

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E. Joe Middlebrooks, Donald B. Porcella,
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INTRODUCTION

Approximately 90 percent of the wastewater lagoons in the United States are located in small communities of 5,000 people or less. These communities, many with an average daily wastewater flow of only 175,000 - 200,000 gallons, do not have the resources to keep men at the lagoon sites throughout the day (38). A high degree of technical knowhow is usually lacking in these communities. Often only periodic inspection or maintenance is carried out by the general municipal work force. Therefore, the development of a relatively inexpensive method that does not require sophisticated and constant operation or extensive maintenance is needed to polish these effluents.

Most regulatory agencies are adopting more stringent water quality standards, enforcement of which will necessitate changes in present treatment methods and the philosophy of wastewater treatment. Small communities utilizing stabilization ponds will be affected most drastically by new standards. Because most communities utilizing ponds are relatively small and installed ponds primarily to avoid operating costs, it is unlikely that modifications requiring significant increases in operation will be acceptable. Therefore, the more sophisticated alternatives for upgrading treatment must be excluded from a practicable solution to solids removal from stabilization pond effluent.

REMOVAL TECHNIQUES

The removal of algae from stabilization pond effluent can be accomplished by many methods, and under certain conditions each process can be shown to be economical and operational. A discussion of the most promising procedures proposed as a means of polishing effluents is presented in the following section. Reasons for including or excluding a process from detailed field evaluation and application in small communities are pointed out. The processes and operations discussed are:

1. Centrifugation
2. Microstraining
3. Coagulation-Flocculation
4. In-Pond Removal of Particulate Matter
5. Complete Containment
6. Biological Discs, Baffles and Raceways
7. In-Pond Chemical Precipitation of Suspended Materials
8. Autoflocculation
9. Biological Harvesting
10. Oxidation Ditches
11. Soil Mantle Disposal
12. Dissolved Air Flotation
13. Granular Media Filtration
14. Intermittent Sand Filtration

Centrifugation

Centrifugation has been found to be an effective process for the dewatering of industrial and domestic sludges (30). Both non-continuous and continuous centrifuges are available; however, the continuous type has the greatest applicability for wastewater treatment facilities. Influent enters the typical continuous centrifuge through feed ports in a stationary feed pipe. It is thrown against the wall of the rotating bowl and the solids that settle out by centrifugal force are transported to the end of the machine by screw conveyer. From 50 percent to 95 percent of the influent solids may be removed by the process and the solids concentration in the sludge cake is normally in the range of 15 percent to 40 percent. Centrifuge operation is characterized by liquid throughput, solids throughput, speed of rotation, and pool depth.

Pilot plant experiments conducted on sewage-grown algae resulted in about 77 percent removal at feed rates of about 3 gpm (43). Solids concentration in the centrate were about 10 percent and the effluent contained about 260 mg/l suspended solids. Centrifugation was found to be an effective means for dewatering algal sludge.

The major disadvantage of centrifugation is the temperamental nature of the equipment. Abrasive solids in the water can cause rapid deterioration of the scroll. Operating problems associated with the relatively sophisticated equipment require considerable time by a skilled operator. Because one of the advantages of stabilization ponds is the low operating expense, it would seem to be impractical to couple them with a unit process which has a major disadvantage of high operating cost.

Microstraining

Microstrainers are low-speed (up to 4 to 7 rpm) rotating drum filters operating under gravity conditions. Filtering fabrics of finely woven stainless steel are fitted on the periphery of the drum. Mesh openings are normally in the range of 23 to 60 microns. Wastewater enters the open end of the drum and flows outward through the rotating fabric. As solids are filtered out of the water, a mat is formed which provides fine filtration so that particles having dimensions smaller than the mesh openings may be filtered out. Slower rotation of the drum results in a higher quality product water. High-pressure jets located outside at the top of the drum continuously backwash the sludge mat into a trough within the drum. Units are built in standard sizes with a wide range of capacities based on filtration rates of 600 to 2,000 gal/sq. ft/hr.

Microstrainers have been used to remove algae from water in reservoirs before water treatment, to remove solids from industrial wastes, and to polish activated sludge effluents (8,32,35,95,102,119). The major problems with the process are incomplete solids removal and difficulty in handling solids fluctuations. These problems can be partially overcome by varying the speed of rotation. In general, drum rotation should be as slow as possible, consistent with throughput and acceptable head differential across the fabric. The controlled variability of drum rotational speed is an important feature of the process, and the speed can be automatically increased or decreased according to the differential head best suited to the circumstances involved.

Another problem associated with microstrainers is the buildup of bacterial and algal slime on the microfabric. This growth can be inhibited by the installation of high intensity ultra-violet irradiation equipment. However, microstrainers may require periodic cleaning.

Pilot plant studies with sewage-grown algae were conducted at flow rates of 50 to 100 gpm (43). Only an extremely small amount of algae was removed even when a filter aid was added. Other investigators, however, have

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found substantial removal of algal cells and other suspended solids in both pilot plant and full scale operations. Scriver (102) reported successful removal of heavy phytoplankton loads from Lake Ontario water prior to treatment by rapid sand filtration. Installation of the 8 mgd microstraining facility reduced filter backwashes by 75 percent. A 2 mgd microstraining facility has been constructed for the removal of microorganisms from lake water before entering a filter plant in Denver (119). The process reduced microorganism concentrations by over 90 percent on the average. Berry (8) reported on the operation of 15 microstrainer plants in Canada and concluded that they are effective and economical for the removal of algae. In a series of nine investigations over a period of years, the average reduction was 89 percent of the plankton. Microstraining has also been effective as a tertiary treatment process. Suspended solids and BOD reductions of 50 percent to over 90 percent have been observed (9,27). During studies using microstraining on effluents from combined sewer overflows, up to 98 percent suspended solids reduction could be obtained (82).

Microstrainers require relatively little maintenance beyond inspection and attention to lubrication, normal to all running machinery. Because of this ease of operation and the evidence that microstraining has a significant removal efficiency for algae, this process may have practical application for the removal of algae from stabilization ponds.

Coagulation-flocculation

Coagulation followed by sedimentation has been applied extensively for the removal of suspended and colloidal materials from water. Lime, alum, and ferric salts are the most commonly used coagulating agents. Floc formation is sensitive to pH, alkalinity, turbidity, temperature, etc. Most of these variables have been studied and their effect on the removal of turbidity in water supplies have been evaluated. However, in the case of the chemical treatment of wastewater stabilization pond effluents the data are not comprehensive.

The coagulation of wastewater has been studied by various investigators. Shuckrow et al. (106) have shown that chemical coagulation with alum and activated carbon of weak sewage (COD value 180 mg/l) is practical. Jar tests indicated good performance at a carbon dose of 600 mg/l, an alum dose of 200 mg/l, and a polyelectrolyte dose of 2.5 mg/l simultaneously. Total chemical oxygen demand (COD) removal was greater than 90 percent. The turbidity of the clarifier effluents was seldom greater than 1 JTU.

Buzzell and Sawyer (10) found that lime treatment of raw wastewaters could effect an 80 to 90 percent removal of PO_4, 50 to 70 percent of BOD, and over 99 percent of coliform bacteria.

Karanik and Nemerow (62) also studied the coagulation of raw sewage and found that the optimum dosage of lime was 300 ppm. The removal results were as follows: the suspended solids in the raw sewage (ranging from 27 to 100 ppm) were reduced to an average of 3.7 ppm or 94.5 percent; the phosphates in the raw sewage (averaging 27.9 ppm) were reduced to 1.8 ppm, a decrease of greater than 93.5 percent. BOD reductions averaged 71.3 percent from an average untreated of 352 ppm to an average effluent of 101 ppm.

Shindala and Stewart (105) investigated chemical treatment of stabilization pond effluents as a post treatment process to remove the algae and to improve the quality of the effluent. They found that the optimum dosage for best removal of the parameters studied was 75 to 100 mg/l of alum. Using this dosage the removal of phosphate was 90 percent and COD was 70 percent.

Ives (58) has shown that algal cells have a negative charge. The density was found to be a function of the viscosity and dielectric constant of the disperse medium, temperature of the medium, and the concentration and valency of the ionic species in the medium. Ives suggested that the removal of algae by chemical coagulation was due to a form of electrical precipitation.

O'Melia and Stumm (89) have shown that pH, time of flocculation, and the anion concentration has an effect on the flocculation process. Tenney (116) has shown that at a pH range of 2 to 4, algal flocculation was effective when using a constant concentration of a cationic polyelectrolyte (10 mg/l of C-31). Golueke and Oswald (43) conducted a series of experiments to investigate the relation of hydrogen ion concentrations to algal flocculation. In this study only H_2SO_4 was used and only to lower the pH. They found flocculation was most extensive at a pH value of 3 which agrees with the results reported by Tenney (116). They obtained algal removals of about 80 to 90 percent. Algal removal efficiencies were not affected in the pH range of 6 to 10 by cationic polyelectrolytes.

The California Department of Water Resources (13) reported that of 60 polyelectrolytes tested, 17 compounds were effective in coagulation of algae and were economically competitive when compared with mineral coagulation used alone. Generally less than 10 mg/l of the polyelectrolytes were required for effective coagulation. A daily addition of 1 mg/l of ferric chloride to the algal growth pond resulted in significant reductions in the required dosage of both organic and inorganic coagulants.

McGarry (73) has studied the coagulation of algae in stabilization pond effluents. He reported the results of a complete factorially designed experiment utilizing the common "jar test." Tests were performed to determine the economic feasibility of using polyelectrolytes as primary coagulants alone or in combination with alum. He

also investigated some of the independent variables which affected the flocculation process such as: concentration of alum, flocculation turbulence, concentration of polyelectrolyte, pH after the addition of coagulants, chemical dispersal conditions, and high rate pond suspension characteristics. Alum was found to be effective for coagulation of algae from high rate oxidation pond effluents and the polyelectrolytes used did not reduce the overall costs of algal removal. The minimum cost per unit algal removal was obtained with alum alone (75 to 100 mg/l). Most significant of the main effects were those of alum and polyelectrolyte concentrations. Time of polyelectrolyte addition had no significant effect; however, more important interactions were those between alum and polyelectrolyte, alum and polyelectrolyte concentrations, between time of polyelectrolyte addition and alum concentration, and between time of polyelectrolyte addition and polyelectrolyte concentration.

Speedy et al. (110) investigated the effectiveness of various prototype unit processes in a water treatment plant in removing algae from a raw water supply. It was concluded that the use of alum as a coagulant is moderately effective in algal removal. However, the use of lime as a coagulant appeared to be more efficient. They also found that different steps of treatment removed different types of algae at different rates.

Autoflocculation of algae has been observed during some studies (43,74,75). The phenomenon involves the natural flocculation and settling of the algae under certain conditions. It has been observed in shallow ponds on warm sunny days. Laboratory studies have indicated that it is possible to bioflocculate algae and remove the flocculated mass so that a relatively solids-free effluent is produced (74,75). *Chlorella* was the predominant alga occurring in the cultures. Laboratory scale continuous experiments with mixtures of activated sludge and algae have produced large bacteria-algae flocs with good settling characteristics (54,55).

Floating algae blankets have been reported in some cases in the presence of chemical coagulants (105,121). The phenomenon may be caused by the entrapment of gas bubbles produced during metabolism or due to the fact that in a particular physiological state the algae has a neutral buoyancy. In a 3,000 gph pilot plant (combined flocculation and sedimentation) a floating algal blanket occurred with alum dosages of 125 to 170 mg/l. About 50 percent of the algae removed was skimmed from the surface (121).

Coagulation-flocculation are not easily controlled and require expert operating personnel at all times. A large volume of sludge is produced and this introduces an additional operating problem that would very likely be ignored in a small community that is accustomed to a minimum of operating and maintaining a wastewater lagoon. Therefore, coagulation-flocculation appears infeasible for application in small communities.

In-pond removal of particulate matter

There are several problems associated with the in-pond removal of particulate matter:

1. The subsequent decay of settled matter and degradation by microorganisms to produce dissolved BOD which would then have an effect on the receiving water.
2. The possibility that settled material will not remain settled.
3. The lack of positive control of effluent particulate matter.
4. The problem of eventually filling in the oxidation pond.
5. The possibility that anaerobic reactions within the settled material will produce malodors.

At first glance, some of these problems can be resolved by rather simple changes in operation. For example, in ponds which are in series, possibly all of the settled material could be removed from the bottom of the last pond and transferred to the anaerobic pond or primary pond where biological degradation is encouraged and malodors are not such a problem. Positive control can be achieved by adding material to the final pond to insure that settling takes place and remains in place. For example, chemicals such as lime, ferric chloride, and alum might be used in this regard. The filling in of a pond is not necessarily as much of a problem as one might think unless chemicals are to be added. Generally, ponds that are used for complete containment have a life expectancy of about 20 years (90). In land short areas, this could be a problem but it might be possible to dredge and remove the solid material after one to two decades have elapsed and restore the pond to its initial status. In areas where land is not so expensive or scarce, this would not be a problem.

These solutions and some of the disadvantages will be discussed in more detail in the section below. In these discussions, the following in-pond mechanisms of particulate removal will be considered: Complete containment, biological discs, baffles or raceways, chemical additions for precipitation, autoflocculation, and biological harvesting.

Slaughterhouse and other meat-packing wastes are generally discharged to anaerobic ponds where complete containment is practiced. Anaerobic ponds generally are considerably deeper, loadings are higher, and there is usually less net accumulation of biomass than ordinary facultative or oxidative type ponds. Essentially only the carbonaceous material is affected, and thus the water is not of sufficient quality for discharge to surface waters. Anaerobic conditions lead to low pH's which are quite corrosive to materials, and plastic liners and plastic piping are usually required. Control of pH is usually necessary for such ponds and additions of soda are often utilized in order to insure that pH and alkalinity are being maintained at the right levels (72). The production of odors,

which occurs whenever sulfates are in any appreciable quantities, is usually minimized if a deep enough pond is utilized.

The problem of non-biodegradable sludge buildup is taken care of by pumping out the sludge on the bottom every four to five years at the beginning of a treatment season followed by reseeding. This sludge buildup occurs at a rate of three to four inches per year in most anaerobic ponds and the major problem is that the ponds soon are not deep enough to contain odors. Lime is frequently added to anaerobic ponds to precipitate sludge and, as a bonus, phosphates. This material is then salable as fertilizer.

However, the practicality of full-scale containment for even small communities which use ponds is virtually nonexistent because of the large volumes of waste produced by the community. The area of land required to insure full containment is too great to be of value. Thus, complete containment is an answer only for high concentration, low volume wastes, such as from packing plants.

Biological discs, baffles, and raceways

The encouragement of attached microbial growth in oxidation ponds is an apparent practical solution for maintaining biological populations and still obtaining the treatment desired. Although baffles are considered useful primarily to insure complete mixing and eliminate the problem of short-circuiting, they behave similarly to the biological discs in that they provide a substrate upon which bacteria, algae and other micro-organisms can grow (87,98). In general, attached growth outcompetes suspended growth if sufficient surface area is available. In anaerobic or facultative ponds with baffling or biological discs, the microbiological community consists of a gradient of algae to photosynthetic, chromogenic bacteria and finally to non-photosynthetic, non-chromogenic bacteria (87,98). In these baffle experiments, the presence of attached growth to the baffles themselves was the reason for higher efficiency of treatment than in non-baffled systems. Raceways are systems set up to provide a shallow pond surface over which water flows at a high velocity. Thus, the current washes out any suspended particulate matter which might tend to develop in such systems, and only attached growth is able to develop. Thus, the requirement for particulate removal is minimized.

None of these biological systems, however, function perfectly. That is, they still produce a certain amount of particulate material from the breaking off and fractionating of filamentous microorganisms. Thus, they would still require a following treatment step for removal of particulate material such as described in the section on chemical precipitation (see p. 6). They have an added disadvantage in that they are relatively expensive; the discs and baffles require a considerable expenditure for construction although this might in part be compensated for by the added rate of treatment and hence higher loadings that are possible (87). The raceway requires either pumping or gravity flow construction. Both methods require considerable capital investment, although the former has lower operating costs. Although an attached growth system has the advantage that it requires little maintenance in terms of the biological operations, its initial cost, subsequent treatment requirement, and unproven capability seems to preclude serious consideration.

In pond chemical precipitation of suspended materials

Several investigations have utilized the addition of specific chemicals to pond effluents to remove particulate matter. The addition of chemicals to the pond directly has the advantage that little additional construction is required. Unfortunately, sludge buildup in a pond is increased immensely due to the addition of chemicals. Thus, periodic pumping of sludge material for maintenance of design pond depth would be required. The pumped sludge has some economic value as a fertilizer if lime is utilized. In addition, recalcination and lime regeneration might allow a lower chemical cost and a source of CO_2 (55) for encouragement of algal growth in the oxidation pond (pH control and CO_2 supply). However, all these processes would force a higher level of complexity and increased capital costs as opposed to keeping maintenance efforts and costs at their lowest value. Thus, in-pond chemical precipitation seems too impractical for evaluation.

Autoflocculation

Autoflocculation is the term for the observance of precipitation of algae and other particulate matter in a pond when the pH rises to very high levels (86). This phenomenon is related to the chemical make-up of the water, in particular the presence of calcium and magnesium carbonates. As the algae remove CO_2, the pH rises to the point where precipitation of magnesium hydroxides and calcium carbonates along with the algae causes removal of the particulate material. However, this is not a practical engineering development at this time. The problems with autoflocculation result from the fact that a separate subbasin is required for settling; very quiescent conditions are required, and a very warm and cloudless day is required to attain the high pH values (upward of pH 11) necessary for autoflocculation.

Biological harvesting

The suggestion that fish and/or higher plant-consuming vertebrates might effectively remove algal materials has proven largely unsuccessful. One of the most significant problems with use of these organisms to harvest particulate matter is excretion of their own fecal matter which in turn later decomposes and results in higher BOD in the effluent than would be permitted. The practical aspects of keeping the biological harvesters in good growing conditions under varying temperature and

flow and oxygen regimes are a further reason that this technique has not been successful. As a means of producing protein, it is a practical concept; however, as a treatment step, it seems unusable.

Oxidation ditches

The operation of oxidation ditches can be thought of as a method of in-pond removal of particulate matter. After the necessary time for BOD removal has elapsed, inflow and mixing are interrupted for about one hour to allow settling of suspended material and the "supernatent" discharged (36). Generally, the oxidation ditch does not develop a significant algal growth which remains in suspension; hence, algal removal is not a problem. Although this method of waste treatment may be feasible, two disadvantages are noted: 1) operational costs are involved as well as significant space requirements, and 2) the method has not gained significant favor in this country, and consequently little operating experience is available to predict performance. Therefore, this process does not appear to be a likely candidate for lagoon effluent polishing.

Soil mantle disposal

A review of the history of sewage treatment indicates that wastewater irrigation was originally developed in the early nineteenth century as a system of both treatment and disposal (83,96,101). In recent years, other forms of waste treatment have become popular. The growth of technical knowledge has led to a reexamination of the possibilities of treatment and disposal of certain industrial, agricultural, and domestic wastewaters through the application of irrigation techniques (26,45,76,84,99).

One of the initial investigations in the United States of sewage filtration was the Dunbar sewage filter. Removal of suspended solids varied with loading conditions. The nature of the suspended matter was an important criteria; with coarse flocculent solids the removal was high, with colloidal solids the removal was smaller (113). Thus the cycle has run its course, the earliest form of waste treatment is now the subject of research and development for the disposal of the water of our time (31,50,56,107,126,127).

However, irrigation with wastewater is not a panacea for the economical treatment and disposal of wastes. Sanitary, aesthetic, economic, ecological, and other technical and practical considerations must be carefully balanced for a sound wastewater irrigation system.

The effect of sewage effluent on the yield of agronomic crops has, in most cases, been found to be beneficial (51,53,78,125,128). Henry et al. (37) obtained a significant increase in the yield of reed canary grass. Huckelekeam (52) obtained excellent crop yields in Israel. Stokes et al. (112) obtained yield increases in Florida amounting to 240 percent for both Napier grass and Japanese cane, when compared with the unirrigated crops, or with the same crops irrigated with well water. Day and Tucker (22,23) and Day et al. (24) in Arizona, obtained beneficial yield effects on small grains which were harvested as pasture forage, as hay or as grain. Parizek et al. (91) at Penn State, have extensively explored the use of wastewater as a spray irrigant on forestry land.

Viruses. More than 100 kinds of viruses are known to be excreted by man and approximately 70 of these have been found in sewage (15). Those that appear to be transmitted through wastewaters are the enteroviruses, poliomyelitis (5,64,67,92,93), coxsackie (14) and infectious hepatitis (25,49,130). There are a limited number of studies of the movement of viruses through granular media (77). These studies showed that rapid sand filtration preceded by coagulation and sedimentation only partially remove virus. The removal of virus from percolating water is largely due to sorption on the soil particles. Soils having a higher clay content sorbed virus more rapidly than those with less clay (33).

Effects on soils. The soil system is composed of gas, water, microorganisms, minerals, and organic matter which form the solid matrix. Experience has indicated that this dynamic system is constantly undergoing physical, chemical, and biochemical interactions. Wastewater applied to the soil mixes with the existing soil water, becoming a part of the system, and may alter the nature and rate of change of the physical, chemical, and biochemical processes in the soil system.

Many insoluble constituents such as suspended minerals, particulate organics, and inorganic precipitates are quickly removed from the liquid by the surface area of the soil. Some of these substances are altered, but some become a permanent part of the soil. Irrigation with wastewaters may produce beneficial or detrimental changes in the soil system.

The microbiological degradation of the suspended solids removed by the soil mantle system has been investigated to some degree with various types of industrial wastes. These studies indicated that the oxidative process for both dissolved and suspended BOD was due to the soil microorganisms, not the enzymes or the bacteria originating in the effluent (124).

Other industrial wastes such as crude oil wastes have successfully been degraded in soil mantle systems. It was found that the mixed population of bacteria, fungi, and actinomycetes found in the soil is more efficient than a single class of microbes (28).

Physical clogging of the soil pores and the resulting loss in the infiltration rate have caused many wastewater soil treatment systems to fail (3,4,60,85,117,129). The potential hazard of high sodium rates to the physical properties of certain soils is of paramount concern. This phenomenon has been studied extensively in an attempt

to improve saline and alkali soils by the proper management of irrigation practices (120). It is well known that additions of organic matter improve the aggregate stability of soils, and wastewaters high in organics have been used to improve the physical properties of soils (79).

It has been known for years that organic matter serves as a granulating agent in soils. Bauer (7) showed that organic matter is conducive to the formation of relatively large stable aggregates and that the effect of organic matter is more pronounced in soils containing small amounts of clay. Small amounts of added organic matter appear to promote large stable aggregates of clay, silt, and sand. The organic content of oxidation pond effluent, both dissolved and particulate (algae) may therefore have a beneficial effect on the soil permeability. Soil microorganisms undoubtedly play a major role in producing organic cementing materials. Martin and Waksman (69) observed that the growth of microorganisms led to the binding of soil particles, and the more readily the substrate decomposed on which the microorganisms had grown, the greater the effect on aggregation. Plant roots appear to be very effective in promoting aggregation by soils. The unusual aggregation of soils in the roots of plants probably is the consequence of mechanical disturbance by plant roots and by wetting and drying, together with cementation by organic compounds (59). The efficiency of spray irrigation of vegetated areas for wastewater disposal is undoubtedly due in part to enhancement of permeable structures by plant roots.

Soil filtration. Filtration is an important mechanism for removing suspended use particles from wastewater effluents applied to the soils and for retaining the microorganisms that facilitate biological decomposition of dissolved and suspended organic matter. Even though the removal of suspended particles from water flowing through soils is easily observed, the processes involved are difficult to describe in simple cases. Listed below are three of the simplest mechanisms which might be combined to describe more complex situations.

Case I - Straining at the soil surface. Under these conditions the suspended particles accumulate on the soil surface and become a part of the filter.

Case II - Bridging. Under these conditions suspended particles penetrate the soil surface until they reach a pore opening that stops their passage.

Case III - Straining and sedimentation. This includes all of the conditions for Case I and Case II except that the suspended particles are finer than half of the smallest pore openings.

These aspects of soil filtration play a very important role in the problems (e.g. clogging) and advantages (virus and organic chemical removal) associated with soil mantle disposal.

Effects on soil chemistry. Irrigation with wastewater has a marked influence on the chemical equilibria in the soil. Organic matter and clay added in the suspended solids can increase the cation exchange capacity of the soil (97). Many of the dissolved chemicals in wastewater influence the suitability of the soil for crop production. Nitrogen and phosphorus compounds have a beneficial fertilizer value when retained in the soil and utilized by the crops. Pollution of groundwater by nitrates which move freely in the soil can be a serious problem (47,114). Release of phosphorus from soils to surface waters can also contribute to pollution (115). Boron content has caused concern in areas where boron-sensitive crops are irrigated with wastewater (111). Toxic concentrations of copper and zinc have apparently accumulated in the soil at sewage farms (100).

The application of soil mantle disposal to upgrading lagoon effluent is limited by soil and groundwater characteristics as well as the chemical characteristics of the lagoon water. However, most lagoons are constructed in areas where land is available and thus capital investment for land mantle disposal is relatively low, and industrial discharge of heavy metals is usually minimal. Further, soil mantle disposal does not create a sludge disposal problem, has a low maintenance and operation cost, and may provide additional irrigation water in arid regions. Therefore, it is felt that soil mantle disposal may be of practical value in upgrading lagoon effluent.

Dissolved air flotation for removal of algae

A comprehensive study (6) of dissolved air flotation for removal of algae was performed at Utah State University to develop a practical engineering technique and to compare results with previous work (40,43). It was found that small quantities of specific coagulants were necessary to improve removal. For example Fe^{+++} (as $Fe_2(SO_4)_3$) improves solids removal (Figure 1). The results of batch tests using ferric sulfate as coagulant were compared to the results obtained by Funk et al. (40) with conditions of 45 psi operating pressure and a controlled pH. No pH control was attempted for USU tests (6); however, the natural pH was approximately 8.7 for these tests, which was somewhat less than for Funk et al. (40). The algal concentrations for their tests are unknown while the results from the USU tests are for 300 mg/l of algae.

In the pH 9.0 curve, which is the closest to the pH of the USU tests, Funk et al. reported approximately a 10 percent additional removal over the results of the USU tests. This could be attributed to a number of possible items including experimental error, type of algae, or the relative efficiency of the two processes. At no time were results of the USU tests able to match the 95 percent removal which they reported at a pH of 3.0 and 51 mg/l of coagulant. The highest removal obtained in these tests was 92 percent at 25 psi and 85 mg/l coagulant with a pH

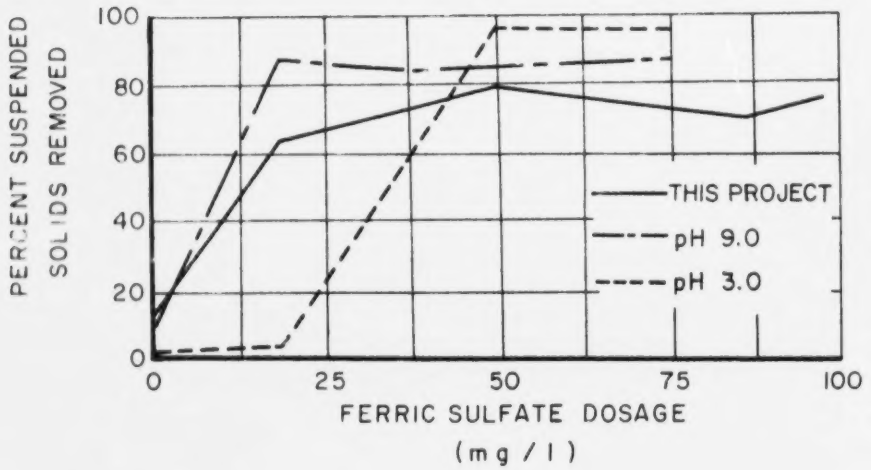

Figure 1. Comparison of results of work by Funk et al. (40) with those achieved in USU tests.

of 8.8. However, the results of the USU tests are believed to be at least equal to those of Funk et al. (40) because pH control, involving the lowering and subsequent adjusting back to at least neutral, was not done and the operating pressure was significantly lower.

Of major concern when using ferric sulfate as a coagulant is the presence of the ferric ion in both the effluent and the removed solids. Regardless of the concentration of coagulant used, there was a visible ferric color in the effluent. At higher concentrations of coagulant, there was a noticeable increase in the intensity of the color, but not in direct proportion to the increased concentration. The removal of the ferric ions through additional treatment procedures might possibly be required before discharge of the effluent or subsequent use of the solids.

Aluminum sulfate produced very good results when used as a coagulant, particularly at the higher concentrations of algae, where up to 95 percent removal was obtained. In comparing the results of the ferric sulfate and aluminum sulfate recycle tests, there seems to be an indication that aluminum sulfate formed a more stable floc, as it was the least subject to a decrease in the percentage removal with increased recycle and the associated increase in turbulence. Aluminum sulfate also showed a generally higher percent removal than ferric sulfate with the same dosage of coagulant. Aluminum sulfate also had an additional advantage in that it did not impart any known toxicity or biostimulation to either the effluent or the solids as did the ferric sulfate.

Of major concern was the wide variation in chemical dosage required to flocculate the algal suspensions sufficiently to achieve approximately the same suspended solids removal results when comparing the bench scale tests with the pilot plant tests.

A number of items were believed to be responsible for the variations observed. These items include:

1. The concentration of algae in the effluent, which was approximately 20 percent higher in the pilot plant tests,
2. The dynamic nature of the pilot plant tests as compared with the rather ideal, static nature of the bench scale tests, and
3. The difference in the algal species being removed (possibly the most influencing factor).

In the bench scale tests *Scenedesmus* was the principal algal species being removed, while in the pilot plant tests *Chlorella* and *Oscillatoria* comprised the dominant algae in the sewage lagoon effluent.

Trainor (118) reported, from a study of the morphology of *Scenedesmus*, that there were large numbers of bristles, which are long appendages more delicate than spines, attached to the cell wall of the *Scenedesmus*. Phase contrast photomicrographs presented in the report showed the bristles forming a random field around the main cell structure that varied from about two to four times the area of the main cell. The field was not solid, but in some photographs showed a fairly dense structure. It is felt that this field of bristles acted somewhat as a flocculated particle in that they were capable of entrapping minute bubbles of air as they precipitated out of solution. This natural trapping action, therefore, decreased the amount of chemical flocculation required to achieve the required removal and thereby caused a decrease in the chemical requirements as compared with other algal species which do not have bristles.

Scenedesmus used in the batch tests were in a completely homogeneous state with little, if any, natural flocculation occurring. However, the algae in the lagoon effluent were in small clusters which were easily distinguished by the unaided eye as individual particles. Although no specific tests were made, it was felt that the configurations of the particles to be removed also influenced the coagulant requirement.

The presence of dissolved COD caused a discrepancy in the percent suspended solids removed as compared with the percent COD removed. Fogg (39) reported that healthy algal cells produced a wide variety of extracellular products, including carbohydrates, fatty acids, polypeptides, amino acids, growth substances, vitamins, antibodies, and enzymes. All of these products are capable of exerting some COD, the total amounts of which may sometimes be as much as that of the cellular material. Fogg (39) further reported that the concentrations of these materials varied considerably between laboratory and field cultures with appreciable amounts of the materials having been found in field studies. Dissolved COD generally averaged about 10 percent or less of the total COD in the batch tests, while in the field tests the dissolved portion was approximately 20 percent of the total COD.

Varma and DiGrano (123) reported that Oswald had proposed that the composition of algae could be described by the empirical formation $C_{7.6}H_{8.06}O_{2.53}N_{1.0}$ and that a general equation for synthesis could be written as:

$$1.0NH_4 + 7.62CO_2 + 2.53H_2O \cdot C_{7.62}H_{8.06}O_{2.53}N_{1.0} + 7.62O_2 + 1.0H^+$$

This equation shows that 1 mg of algae theoretically requires 1.58 mg of oxygen to become oxidized to CO_2 and H_2O. In attempting to check this theoretical relationship, Varma and DiGrano performed four groups of tests and found an average value of 0.67 mg of O_2 per mg of algae. This compares with a value of 1.11 mg of O_2 per mg of suspended solids obtained from the tests that were run in conjunction with the Utah State University project (6). The COD versus suspended solids ratio for the bench scale tests also ran approximately the same ratio with the exception of the first three weeks of the tests when the ratio was approximately 1.50 mg of O_2 per mg of suspended solids. The results from the pilot plant tests were considerably less, however, as the average was 0.81 mg of O_2 per mg of algae after deduction of the dissolved COD. Although these results do not agree with the theoretical values of Oswald, they do represent a significant improvement over the results previously obtained by Varma and DiGrano.

Important parameters in design of a flotation system are the hydraulic loading rate, including recycle, concentration of suspended solids contained within the flow, and the air-to-solids ratio required to effect efficient removal. For the Utah State University pilot plant tests the maximum hydraulic loading rate was found to be 2.35 gal/min/sq. ft (6). The most efficient air-to-solids ratio was found to be 0.019. The solids concentration during the pilot plant tests was 125 mg/l. Although the number of pilot plant tests performed were admittedly limited in number, it is felt that they do represent valid design data for similar situations.

These test values compare with suggested trial design values of 1 to 4 gpm hydraulic loading and .01 to .03 air-to-solids ratio for general industrial wastes as provided by the manufacturers of flotation equipment. These values are of necessity of a general nature, but they do give an operational range into which the test values fall.

In combined flotation-sedimentation pilot plant tests at Windhoek, Southwest Africa, van Vuuren and van Duuren (121) reported hydraulic loading rates ranging from .275 to .75 gal/min/sq. ft. As their flotation was dependent upon the natural dissolved oxygen, no air-to-solids ratios were reported. They also reported that it was necessary to use from 125 to 175 mg/l of aluminum sulfate to flocculate the effluent which varied from 25 to 40 ppm algae. This compares with the 175 mg/l required to flocculate 125 ppm algae in these tests. Subsequent reports on the total flotation system by van Vuuren et al. (122) reported dosages of 400 mg/l aluminum sulfate were required to flocculate a 110 ppm algal suspension sufficiently to obtain a removal that was satisfactory for consumptive reuse of the water.

Although data for comparison of aluminum sulfate dosage are limited, the results of these tests do indicate that substantial removal could be achieved with considerably smaller dosages than previously reported for a continuous flow operation and similar solids content.

In these studies the solids concentration was approximately 1 percent from the pilot plant, but this could be increased to 2 percent by allowing a second flotation to occur in the skimmings receiving vessel. Golueke and Oswald (43) reported a high moisture content, 98 to 99 percent, in their studies of various methods of algae concentration. They further noted that the solids content could be increased to 10 to 15 percent by dewatering the algal slurry on a sand bed. Also van Vuuren et al. (122) reported that the flotation layer on their plant contained 3.7 percent solids. Thus the results of these tests, although not exceptional, do generally agree with the limited amount of published data available.

Dissolved air flotation does not satisfy the basic requirements of simplicity and ease of operation that would be required in small communities. In addition the process is relatively expensive and requires the addition of coagulants to obtain successful algae removal. The addition of coagulants significantly increases the bulk of the sludge to be removed and dewatered.

Granular media filtration

Granular media filtration is probably the most overlooked unit operation for upgrading wastewater quality. The filters are generally used for liquid-solids separation. The simple design and operation of this process makes it applicable to wastewater streams containing up to 200 mg/l suspended solids. Automation based on easily measured parameters gives minimum operation and maintenance costs.

Filtration rates can range from 25 to 50 gpm per sq. ft. for coarse solids to 2 to 5 gpm per sq. ft. for colloidal suspensions. The versatility of filter bed designs (media sizes and depths) is such that nearly any effluent quality can be achieved. In addition, granular media filters can be used as chemical treatment units by adding inorganic coagulants (e.g., alum) and/or polymers to achieve both a high degree of liquid-solids separation and precipitation of other pollutants such as phosphorus.

Oil removal is another application for granular media filters. They can handle free oil and, to a limited extent, emulsified oil. Where both suspended matter and oil must be removed, this process has been very successful.

The wastewater is passed through one or more layers of coal, sand, garnet, etc. As the wastewater flows through the granular material, suspended solids are removed by physical screening, sedimentation and interparticle action. The liquid headloss increases until the filter reaches its removal capacity. At this point, the wastewater flow is stopped and the filter must be cleaned.

In wastewater applications, cleaning the media is difficult because of slime growths throughout the filter media. These growths and the collected solids can be removed by a combination of air-water backwash. Air is first added to expand the bed and scrub the media by particle collision. This is followed by hydraulic flushing to remove the waste materials and restratify the media according to specific gravity of the media particles.

Precoat filters, either semicontinuous pressure designs or continuous vacuum types, provide a similar "bed" for solids removal. The precoat material is wasted together with the filtered solids, and consequently, the economics of this operation must be reviewed carefully to determine if they are more favorable than those of a corresponding granular filter. One distinct advantage of the precoat unit is that filtrate clarity is almost always less than 1 mg/l of suspended solids.

Effluent quality and costs for granular media filtration are summarized in Table 1. A typical device available on the open market is shown in Figure 2.

Granular media filtration offers the advantages of automatic operation, sparkling clear effluent, and the addition of nutrient removal if such a requirement is imposed in the future. The process appears to be economically feasible in the removal of algal cells from lagoon effluents.

Intermittent sand filtration

Sand filtration of water is by no means a recent discovery. Literature sources have recorded the first efforts of man's attempt to improve the quality of his drinking water by slow sand filtration as early as 1828. The success of these efforts was such that many large cities in the world adopted the slow sand filter as means to improve the quality of their drinking water. This treatment system has well stood the test of time with records of improvements on the basic design being made as recently as 1952 (61). These improvements were solely to meet the rising volume of water demanded by a growing population.

One of the points of major importance more recently ascertained was the filters' ability to remove a large percentage of bacteria from the culinary water (94). Coupling this with the filters' ability to improve the overall physical appearance of the water, it can be seen that its decline in use was not due to its performance but was due primarily to its rate of performance.

With the use of culinary waters came the production of wastewater. Early efforts to stabilize wastewaters were also through the use of sand filtration. It was probably felt that if noticeable improvement to culinary water could be obtained by sand filtration, at least some improvement in wastewater could be obtained using similar means. Thus, in 1888, the first intermittent sand filter in the U.S. appeared on an experimental basis in Lawrence, Massachusetts (70). Results of this study plus additional assets of the area combined to provide a method of satisfactory treatment of domestic wastewaters. In most cases, use of such filters was limited by two factors; 1) availability of natural sands of the necessary specifications, and 2) the acquisition of the large land areas necessary. At that time, the New England area had adequate supplies of both, so, therefore, the use of the intermittent sand filter was primarily in New England for many years.

Due to this limited application and world problems, little additional information on intermittent sand filtration was published from pre World War I to approximately 1945. After this period, it once again appeared in the literature as a potential solution to unique wastewater problems associated with the rapidly growing residential communities in Florida. The problem in Florida was that of treatment of domestic wastewater volumes associated with subdivisions and mobile home courts. These relatively small communities were springing up almost everywhere in Florida. It was then necessary to develop a method of treatment which would be economic, practical,

Table 1. Effluent quality and costs for various treatment processes.

Process	S.S. mg/l	COD mg/l	BOD_5 mg/l	Turb. JTU	P mg/l	N mg/l	Cost Dollars/MGD		Reference
							1 MGD	10 MGD	
Chemical Treatment (Solids Contact)	0-7	17	2.9-5	0.2-2.9	0.08-0.9	5-10.7	60-130	36-90	19,44,65,108
Granular or Mixed Media Filtration W/Chem.	0-5	13-17	3.1-5.8	0.2-10	0.05	5	50	24-40[a]	6,20,63,103,104
Intermittent Sand Filt.	0-3	-	3-5	-	-	-	30[f]	-	57
Sand Filtration W/Chem. Coag.	2-5	26	2-3	0.8-3.5	0.15-1.5	-	-	-	48
Extended Aeration	35	-	20	-	-		-	200	103
Total Containment	-	-	-	-	-	-	40-55	-	81
Activated Carbon	0.6	10-12	1.0	1.2	0.3	6.6	160	27[b]-179[c]	20,29,34,71,108
Reverse Osmosis		0-1.0	-	0.27	0.2*	3.5**	-	300-600	17,29,63,88
Electrodialysis		8.0	-	-	7.8*	8.2**	200	70-500	17,29,108,109
Ion Exchange	-	3.7	-	0.0	8.8*	4.2**	-	170-220[d]	1,17,29
Dissolved Air Floatation	6	3	-	-	-	-	110	40-70 60[e]	6
Microstraining	5	6	3	-	-	-	18	15	2,16,18
Ultrafiltration	0	20	< 1	< 0.1	-	-			66

*PO_4 only

**NH_3-NO_3 only

a. For 7.5 MGD plant
b. For 7.5 MGD plant
c. Amortization $3,359,000; 20 yrs at 5%
d. Amortization $1,370,000; 20 yrs at 5%
e. For 20 MGD plant
f. Amortization $90,000; 20 yrs at 5%

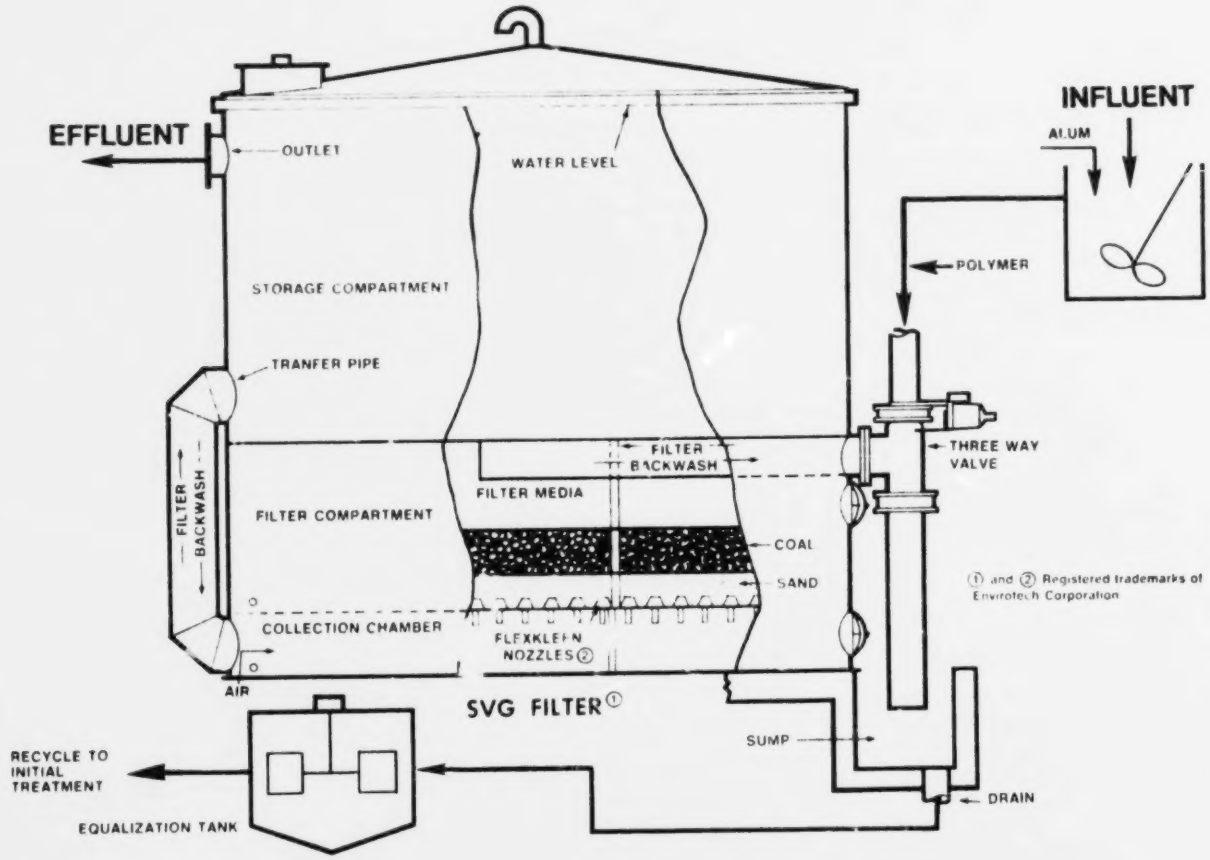

Figure 2. Flowsheet for suspended solids removal by granular filtration. By addition of coagulants, phosphates, and other pollutants are precipitated.

and produce a satisfactory effluent for these widespread, small residential populations.

Work was then initiated at the University of Florida and it was from this work that much of the design and operational data has originated. Such factors as temperature, hydraulic loading rates, dosing periods, sand size, and depth of sand bed were studied (42,46). The effects of these variables were monitored through BOD, total nitrogen, and suspended solids analysis. There was also significant study undertaken to describe the microbial populations and their influence in the treatment of settled domestic sewage by intermittent sand filtration (11,12). Information gained through this study that would aid in future design of intermittent sand filter treatment plants was also published (41).

From the early literature on slow sand filters, the accounts of the intermittent sand filter studies of New England, and the more modern efforts of Florida researchers, various general design texts on the subject were published during the fifties. These general sources appear to be the most recent works on the subject, and they, too, deal primarily with the treatment of primary or primary settled sewage. There is very little information on the performance of the intermittent sand filters as a polishing unit. It is, therefore, felt that a need does exist to study the intermittent sand filter's ability to perform as a polishing unit.

At present, work has been undertaken to evaluate the intermittent sand filter as a process to upgrade existing wastewater treatment facilities in Utah. Results of a laboratory and field study have been encouraging. Wastewater treatment plant effluent polishing by intermittent sand filtration was found to be capable of consistently producing an effluent with BOD and SS concentrations of less than 5 mg/l. Sand size was found to be related to the quality of effluent produced as well as the time of operation afforded before plugging occurs.

SUMMARY AND CONCLUSIONS

The removal of particulate matter from wastewater lagoon effluents is a necessity to prevent downstream pollution of surface waters, and lately state and federal regulatory agencies are beginning to enforce regulations requiring particulate removal. Criteria for candidate processes include ease of operation, minimum maintenance and cost, dependability of operation and efficiency of particulate removal. The last point includes preventing the possibility of recycling of BOD and possibly nutrients as a result of decay of the particulate organic matter.

Centrifugation has been found to be an effective process for dewatering industrial and domestic sludges. Pilot plant experiments on sewage-grown algae indicate that this process may also be an effective means of dewatering algal sludge. However, because operating problems associated with the relatively sophisticated equipment require considerable time by a skilled operator, it is not practical for application to small stabilization ponds.

Microstrainers have been used successfully in numerous applications for the removal of algae and other suspended material from water. In a series of nine investigations over a period of years, an average removal of 89 percent of net plankton was observed. The major problems associated with this process are the difficulty in maintaining a consistent effluent quality during fluctuations in influent loading and the buildup of bacterial and algal slime on the micro-fabric. Microstraining requires relatively little maintenance beyond periodic inspection, cleaning, and lubrication. It may have practical application for the removal of algae from stabilization ponds.

Coagulation-flocculation, followed by sedimentation, has been applied extensively for the removal of suspended and colloidal material from water. However, the effectiveness of the process on algal cells depends, to a significant extent, on the type and physiological state of the cells and may fluctuate widely. Coagulation-flocculation is not easily controlled and requires expert operating personnel. Also a large volume of sludge is produced. This process appears infeasible for application in small communities.

The criteria of ease of operation, minimum maintenance and cost, and dependability of operation cause many of the methods discussed above to be excluded from further consideration and evaluation. For example, in-pond removal of 1) particulate matter using biological discs, baffles, and raceways, 2) in-pond chemical precipitation, and 3) autoflocculation suffers not only from lack of operating information but from dependability of operation and the possible subsequent recycling of BOD due to decay and washout of soluble organic matter.

Complete containment is not feasible because of the large land area required, thus being costly. Biological harvesting is costly, relatively ineffective, and requires considerable management and operating skill. Oxidation ditches also require considerable operation and lack of design familiarity counts against the design and operational dependability. Dissolved air flotation requires chemical addition and considerable maintenance. Hence it does not meet the cost criteria.

The use of the soil mantle for polishing effluents from both domestic and industrial wastewater treatment plants must be seriously considered based upon effluent restrictions, and the cost of the treatment facilities. The questions which remain to be answered concerning spray irrigation systems are: 1) Virus transport and viability in the aerosol mist; 2) nitrification conditions within the soil mantle system; 3) salt buildup within the soil mantle system; 4) accumulation of heavy metals within the soil mantle system; and 5) viruses and bacteria adsorption and inactivation within the soil mantle system. Basic research will answer many of the questions raised, but many of the questions will require site specific investigations. A soil mantle treatability study should include use of actual effluent, the soil system proposed, and the environmental constraints. The use of the soil mantle for treatment of municipal and domestic effluents has come under considerable criticism of late. This, in part, can be attributed to lack of consideration for environmental consequences by many of the promoters of land disposal as well as the scale of operation without regard to localized problems due to toxic material accumulation, and site specific topographical, hydrological and meteorological considerations.

In granular media filters, wastewater passes through one or more layers of a granular media, such as coal, sand or garnet. The suspended material is removed from the wastewater by physical screening, sedimentation, and interparticle action. For separation of algal cells from lagoon effluents, granular media filtration offers the advantages of automatic operation, clear effluent, nutrient removal, and economic operation.

The use of intermittent sand filters to upgrade water quality dates back to 1828. Although it produces a high quality effluent, intermittent sand filtration is not widely

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used today because it requires a low loading rate. There is very little information available on the performance of intermittent sand filters as polishing units. However, research currently underway at Utah State University indicates that this process is readily adaptable to the removal of algal cells from lagoon effluents. It offers the advantages of a clear effluent, low effluent BOD and economical operation.

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